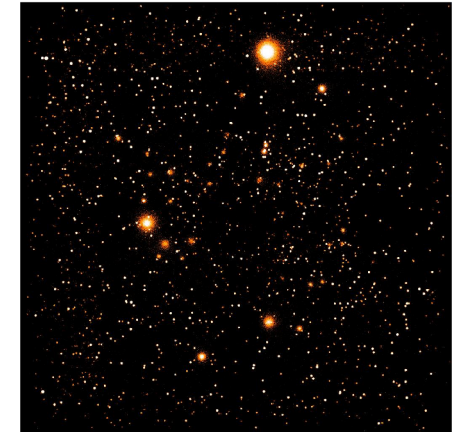
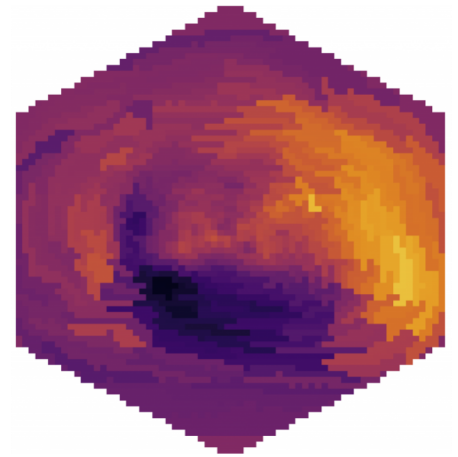


# ATHENA:

*Athena*: The Advanced  
Telescope for High Energy  
Astrophysics



Rob Petre  
NASA Athena Project Scientist  
NASA / GSFC



# Outline

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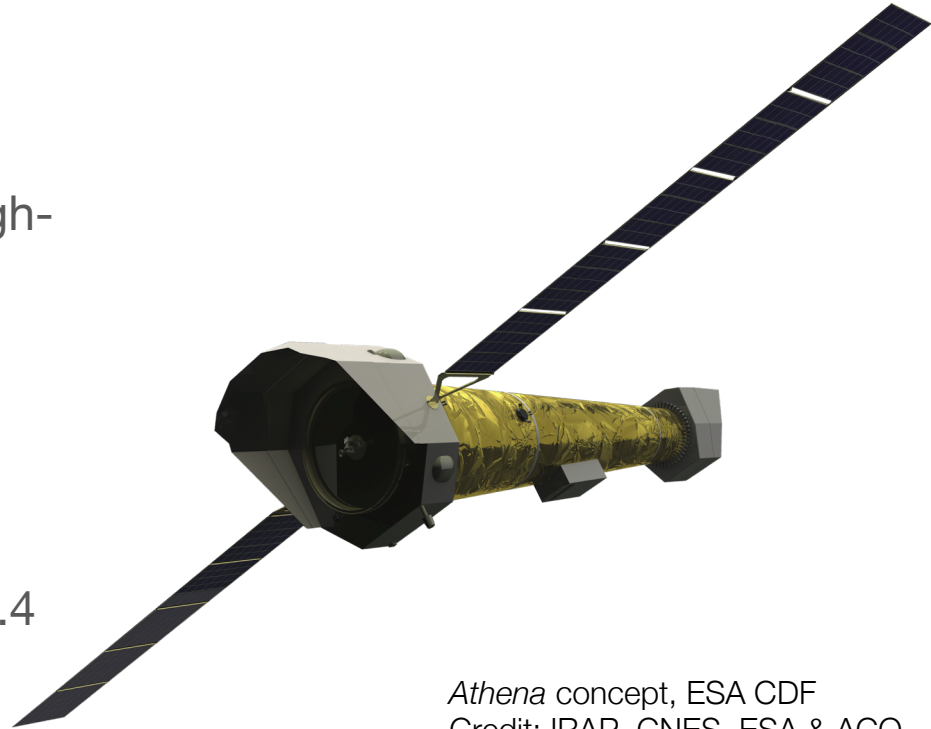
- *Athena* overview
- *Athena* science: the Hot and Energetic Universe
- Mission concept & payload
- NASA contributions and opportunities for US scientists
- Project development status
- Outlook



# Athena mission concept

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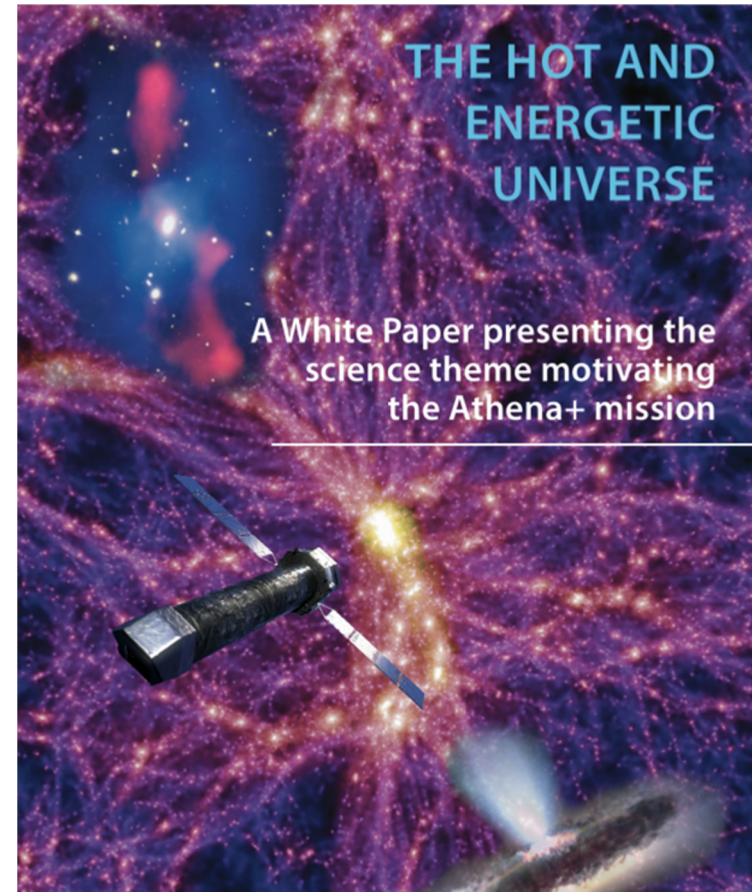
- Single telescope, using Si pore optics. 12m focal length
  - WFI sensitive imaging & timing
  - X-IFU spatially resolved high-resolution spectroscopy
- Movable mirror assembly to switch between the two instruments
- Launch early 2030s, Ariane 6.4
- L1 halo orbit (TBR)
- Lifetime: 4 yr + possible extensions (designed for 10 yr)



*Athena* concept, ESA CDF  
Credit: IRAP, CNES, ESA & ACO

# The Hot and Energetic Universe

- The Hot Universe: How does ordinary matter assemble into the large-scale structures that we see today?
  - >50% of the baryons today are in a hot ( $>10^6$  K) phase
  - There are as many hot ( $> 10^7$  K) baryons in clusters as in stars over the entire Universe
- The Energetic Universe: How do black holes grow and influence the Universe?
  - Building a SMBH releases 30× the binding energy of a galaxy
  - 15% of the energy output in the Universe is in X-rays



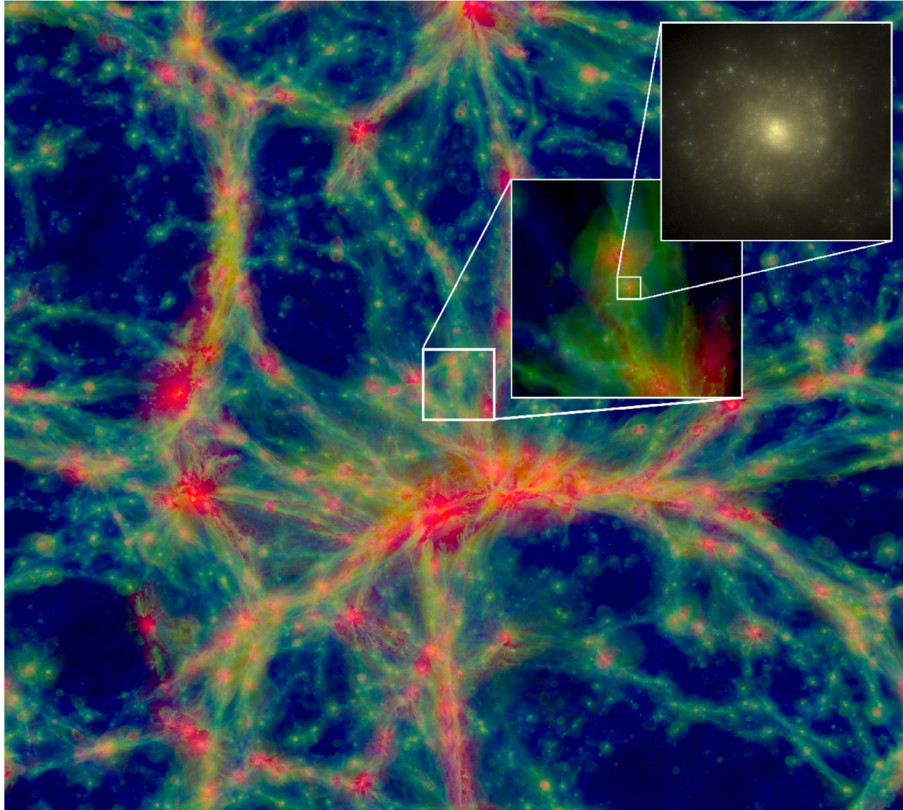
[Nandra, Barret, Barcons et al. arXiv:1306.2307](https://arxiv.org/abs/1306.2307)



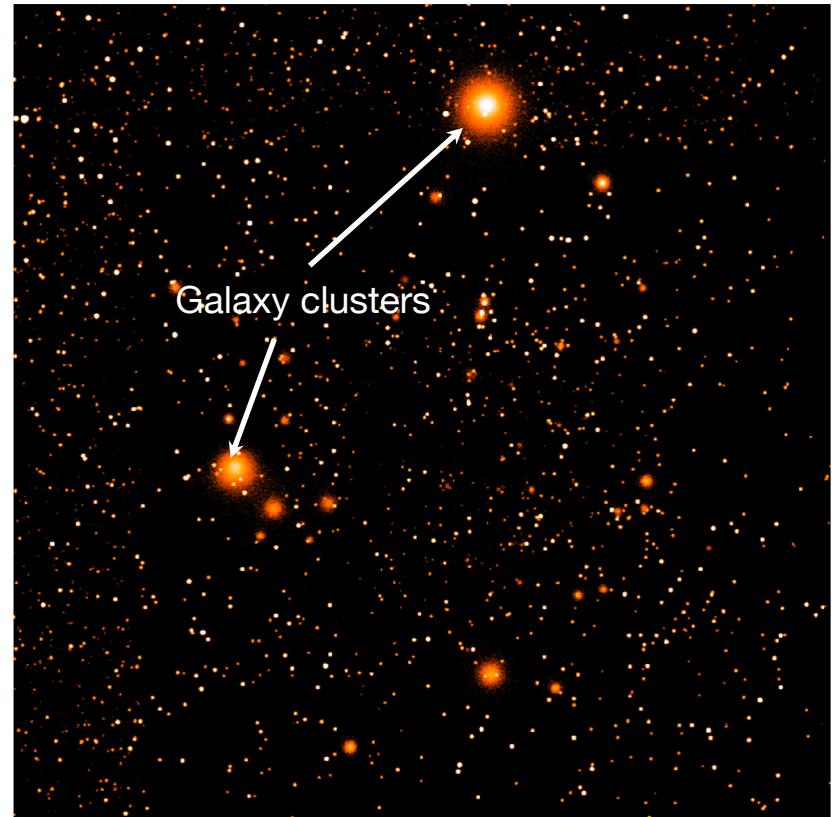
# The Hot Universe – baryonic assembly

EAGLE cosmological simulation

$T < 10^{4.5} \text{ K}$   $10^{4.5} \leq T \leq 10^{5.5} \text{ K}$   $T > 10^{5.5} \text{ K}$



Schaye et al. 2015

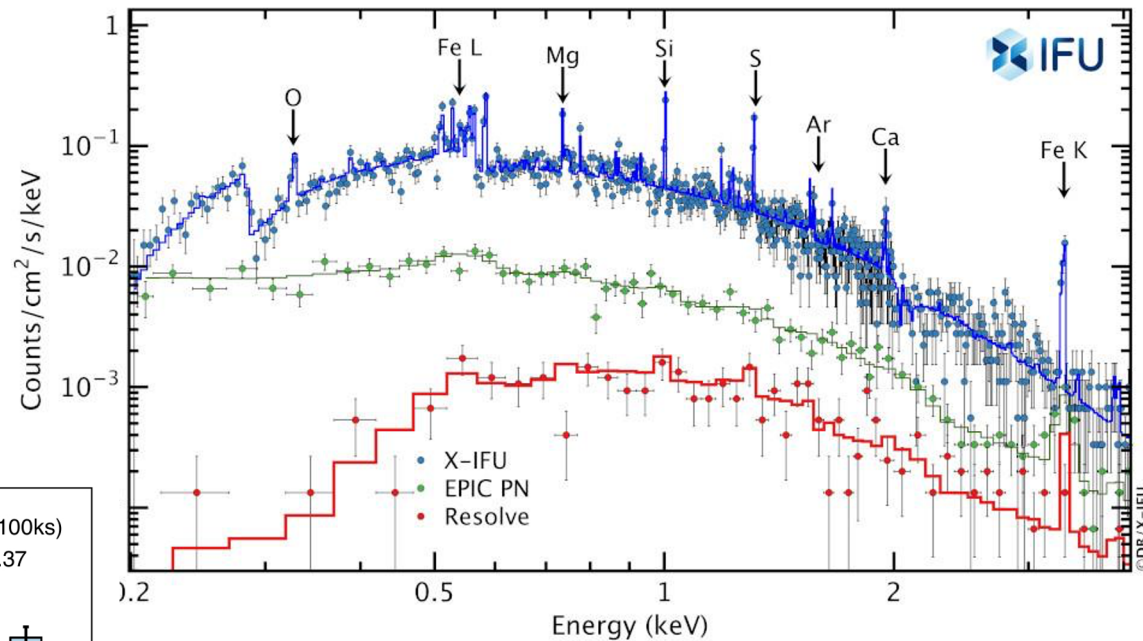


*Athena/WFI 0.5 Ms simulation*  
A.Rau/WFI team

# Chemical evolution

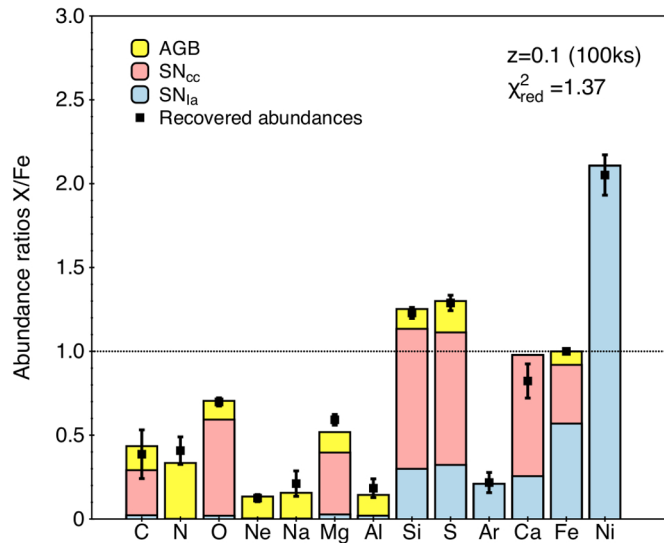
- Clusters of galaxies are closed boxes, all gas is virialized in the DM potential well
- Cosmic chemical evolution traced by cluster gas
- Constraints on origin of elements and IMF

Galaxy group @ $z=1$   
150ks *Athena*/X-IFU



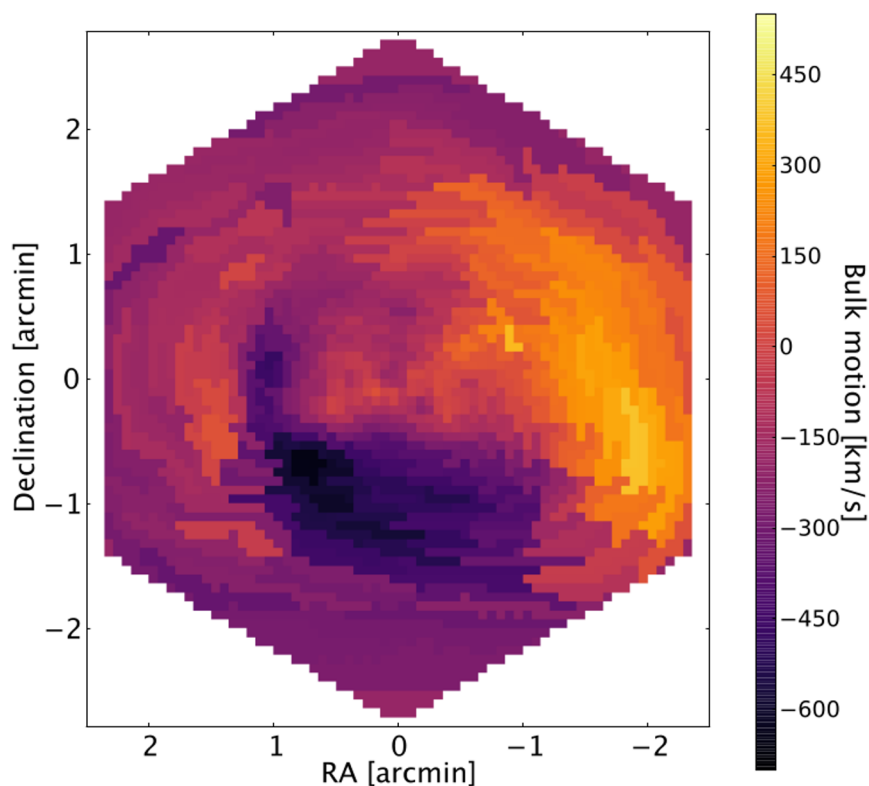
Credits: data courtesy of Etienne Pointecouteau . X-IFU Consortium.

Image courtesy of E. Cucchetti from the X-IFU Consortium. Simulations courtesy: S. Borgani, V. Biffi, K. Dolag, L. Tornatore, E. Rasia - INAF Trieste.



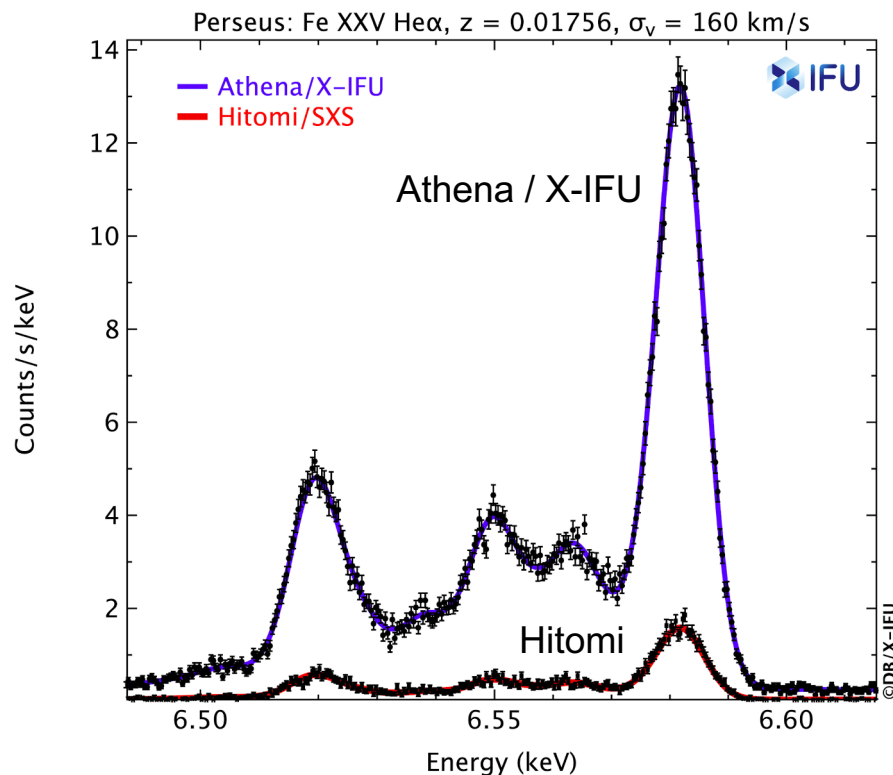
# Cluster bulk motions & turbulence

- *Athena* will measure gas bulk motions and turbulence down to 20 km/s
- X-IFU will have larger collecting area, higher spectral resolution, and larger field of view than Hitomi/SXS or XRISM/Resolve



Simulation of the bulk motion map of the hot gas in a galaxy cluster at  $z=0.1$

Credits: X-IFU team (E. Cucchetti, IRAP)

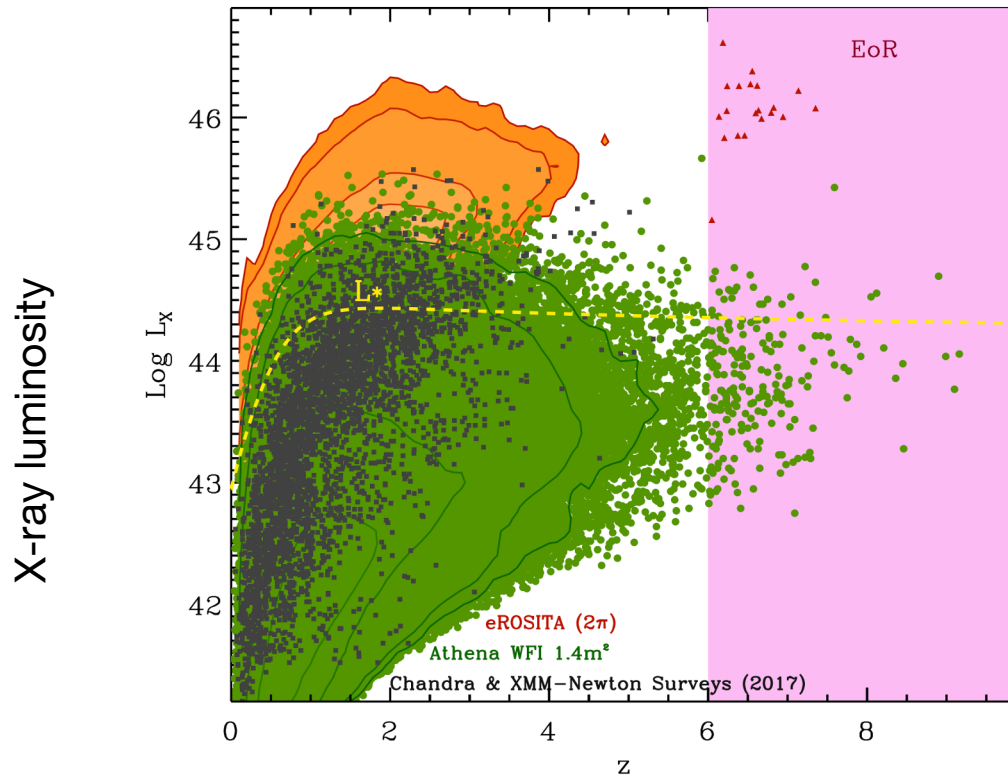


Fe XXV line compared to the one measured with Hitomi Soft X-ray Spectrometer (SXS)

Credits: X-IFU consortium

# The history of SMBH growth

AGN  $L_X$  versus  $z$  plane



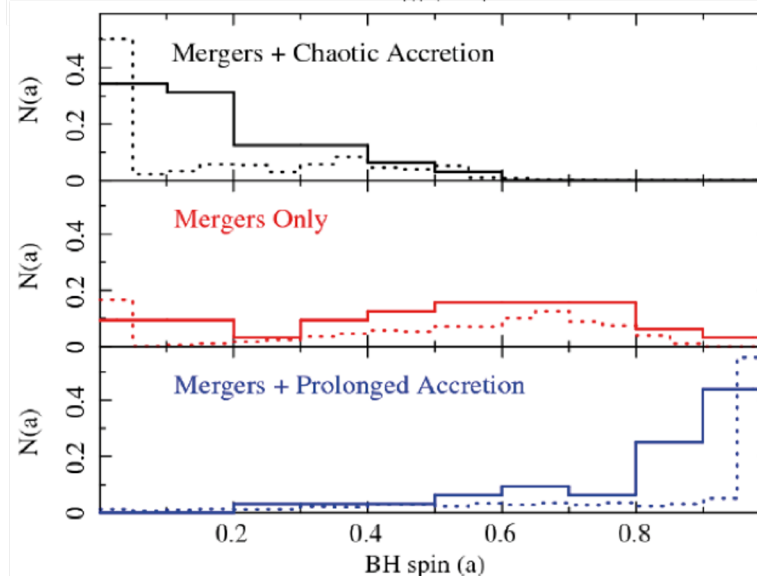
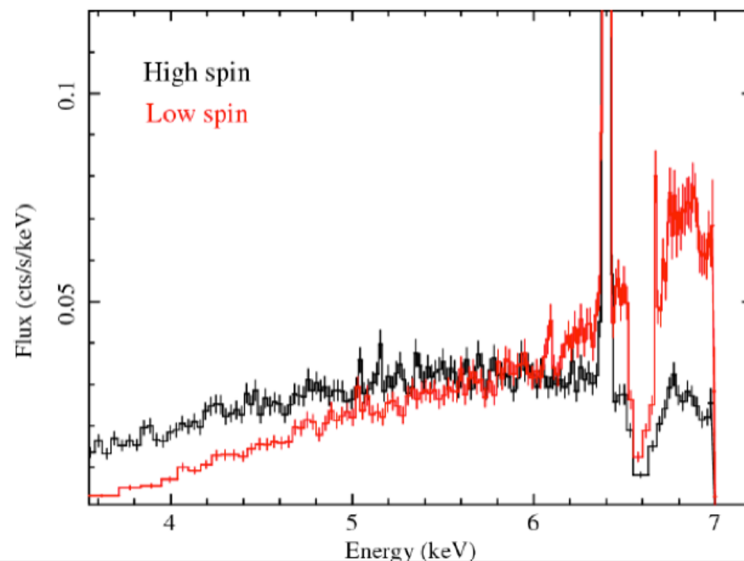
Only most luminous  
/massive QSOs  
expected in opt/IR  
surveys

X-rays needed  
to signpost typical  
and obscured AGN

Aird, Comastri et al. 2013 arXiv1306.232  
Updated by Andrea Merloni (MPE) (2017)

# SMBH growth: accretion vs mergers

- SMBH spin distribution is highly sensitive to SMBH growth history
  - Accretion spins up SMBH
  - Mergers & chaotic accretion spin down SMBH
- A SMBH spin survey with *Athena* will reveal dominant SMBH growth mode
- Athena will be able to perform the spin survey to lower fluxes and in shorter times for bright sources than any planned or current X-ray observatory



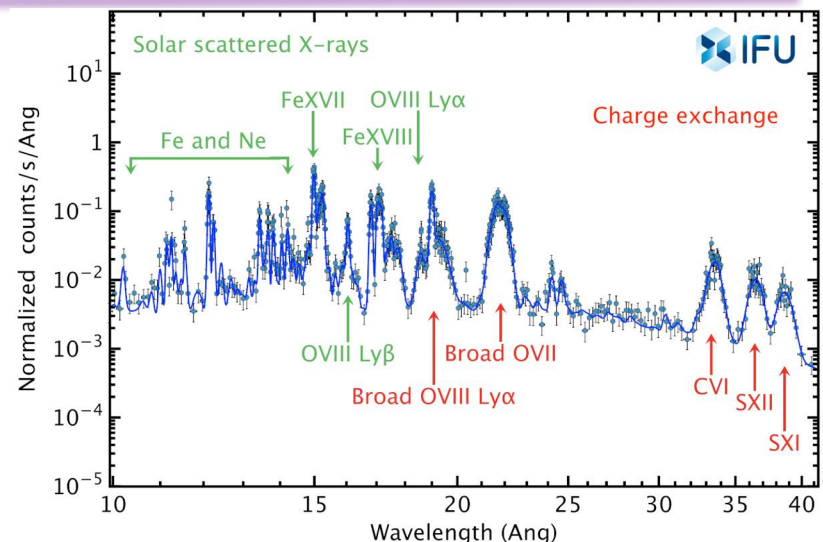
Dovciak, Matt et al. 2013: arXiv 1306.2331  
simulations by G. Miniutti



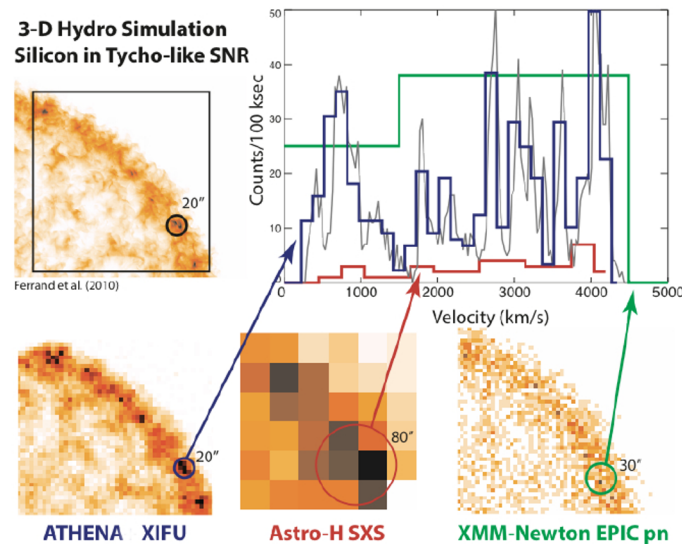
# Observatory and discovery science

- Planets and solar system bodies
- Exoplanets: magnetic interplay
- Star formation, brown dwarfs
- Massive stars: mass loss
- Supernovae: explosion mechanisms
- Supernova remnants: shock physics
- Stellar endpoints (NS)
- Interstellar medium
- Dark matter candidates ...

~ 2/3 (TBC) of the *Athena* nominal operational life will be allocated to the international astronomical community through a competitive peer review process



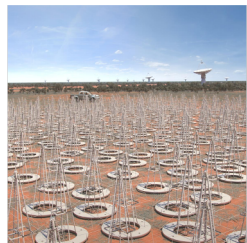
Data courtesy of Graziella Branduardi-Raymont.  
Credits: X-IFU consortium.





# Athena in the framework of the early 2030s

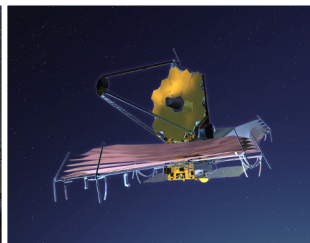
SKA



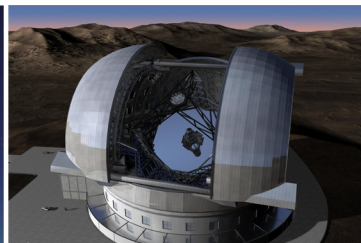
ALMA



JWST



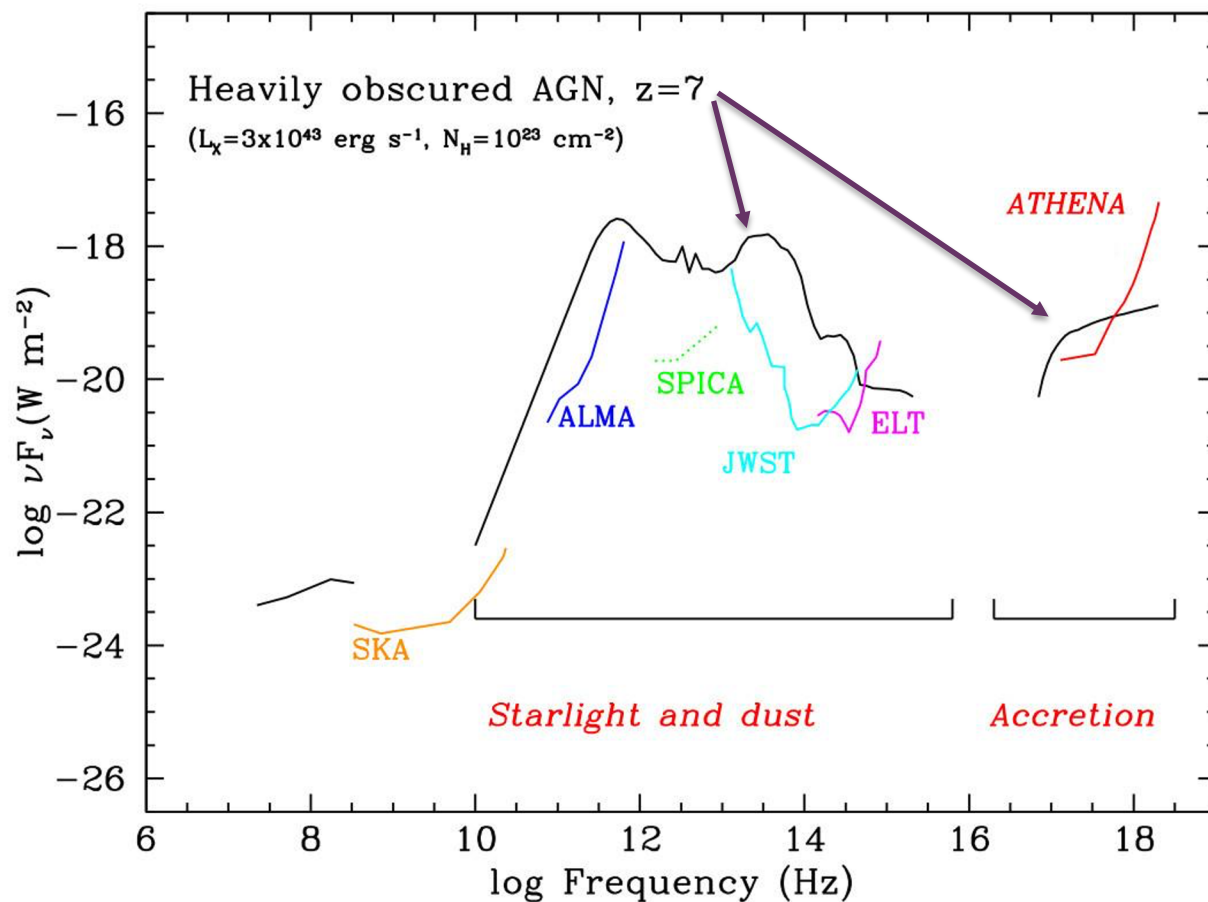
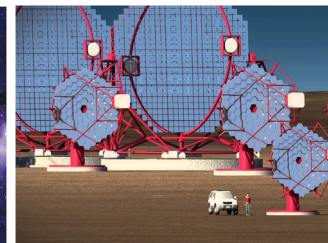
ELT



Athena



CTA



Courtesy: M. Brusa. 2019.

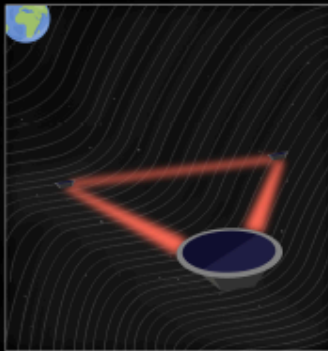
Athena will fill a gaping hole in the multi-wavelength and multi-messenger parameter space in the early 2030's

# LISA/Athena synergy

## → HOW CAN LISA AND ATHENA WORK TOGETHER?

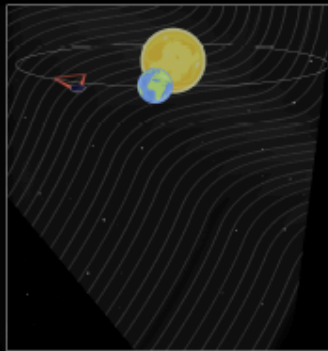


About 1 month  
before



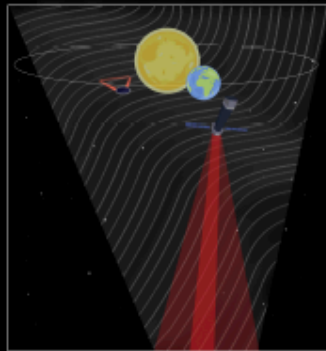
LISA detects gravitational waves from **supermassive black holes** spiralling towards each other and calculates the date and time of the final merger, but the position in the sky is unknown

2 weeks  
before



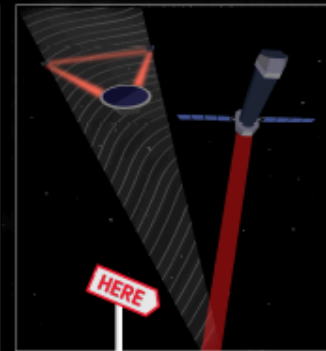
As the inspiral phase progresses, the gravitational wave signal gets stronger; meanwhile, LISA collects more data as it moves along its orbit, providing a **better localisation** of the source in the sky

1 week to  
several hours before



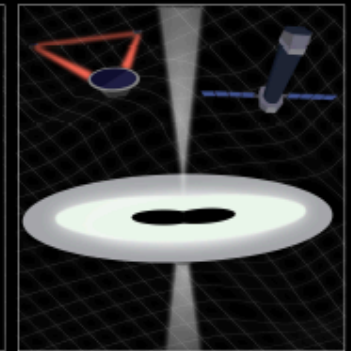
LISA indicates a **fairly large patch in the sky** (around 10 square degrees) where the source is located, so that Athena can start scanning this region to look for the source with its Wide Field Imager (WFI)

A few hours  
before



LISA locates the source to within a **smaller portion of sky**, roughly equal to the size of the Athena WFI field of view (0.4 square degrees); Athena stops scanning, and starts staring at the most likely position of the source, witnessing the final inspiral and merger of the black holes

During and after  
the merger



While LISA detects the **gravitational wave 'chirp'**, Athena can observe any associated **X-ray emission** and might witness the onset of **relativistic jets**: if this happens, Athena and LISA may witness the birth of a new 'active galaxy'

#Space19plus #AnsweringTheBigQuestions

Space19

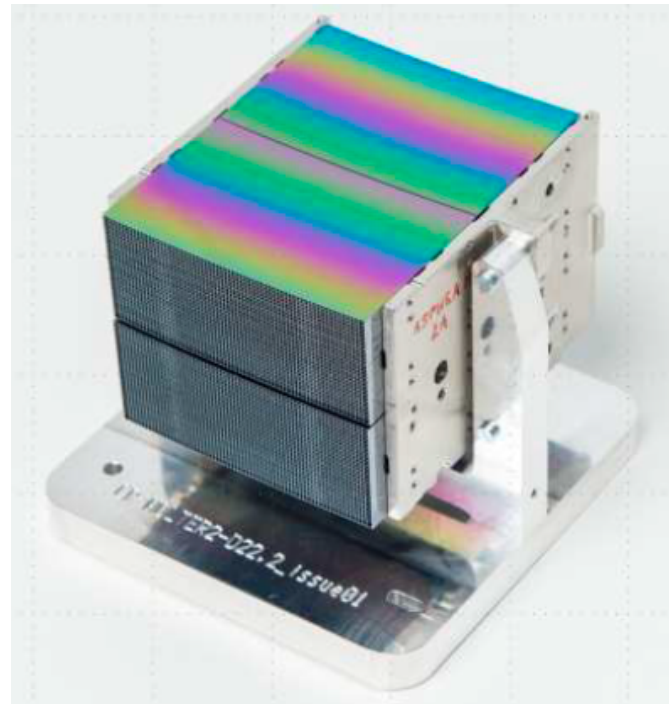
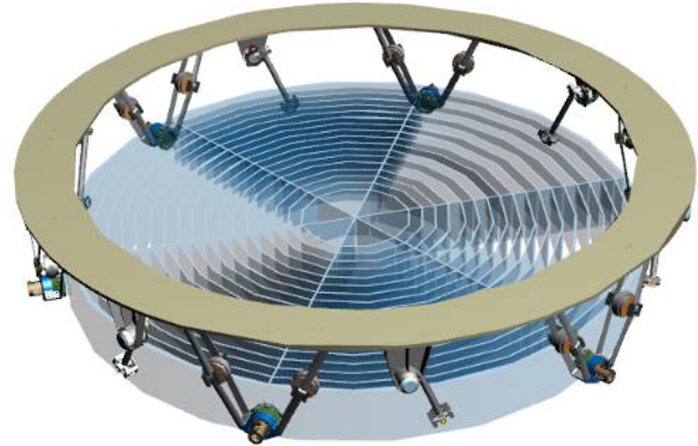
# Athena Science Requirements

Parameter	value	enables (driving science goals)
Effective area at 1 keV	$\geq 1.4 \text{ m}^2$	Early groups, cluster entropy and metal evolution, WHIM, high redshift AGN, census AGN, first generation of stars
Effective area at 6 keV	$0.25 \text{ m}^2$ (TBR)	Cluster energetics (gas bulk motions and turbulence), AGN winds & outflows, SMBH & GBH spins
PSF HEW ( $\leq 7 \text{ keV}$ )	5'' on axis (TBR), 10'' off axis	High z AGN, census of AGN, early groups, AGN feedback on cluster scales
X-IFU spectral resolution	2.5 eV 0.2-12 keV	WHIM, cluster hot gas energetics and AGN feedback on cluster scales, energetics of AGN outflows at $z \sim 1-4$
X-IFU FoV	5' effective diameter	Metal production & dispersal, cluster energetics, WHIM
X-IFU background	$< 5 \cdot 10^{-3} \text{ counts/s/cm}^2/\text{keV}$ 2-10keV	Cluster energetics & AGN feedback on cluster scales, metal production & dispersal
WFI spectral resolution	$< 80 \text{ eV}$ (1keV) & $< 170 \text{ eV}$ (7keV)	GBH spin, reverberation mapping
WFI FoV	40' x 40'	High-z AGN, census AGN, early groups, cluster entropy evolution, jet-induced cluster ripples
WFI count rate	1 Crab $> 80\%$	GBH spin, reverberation mapping, accretion physics
WFI background	$< 5 \cdot 10^{-3} \text{ counts/s/cm}^2/\text{keV}$ 2-7keV	Cluster entropy, cluster feedback, census AGN at $z \sim 1-4$
Recons. astrometric error	1'' (3s)	High z AGNs
GRB trigger efficiency	50%	WHIM
ToO reaction time	$\leq 4 \text{ hours}$	WHIM, first generation of stars



# The *Athena* X-ray mirror

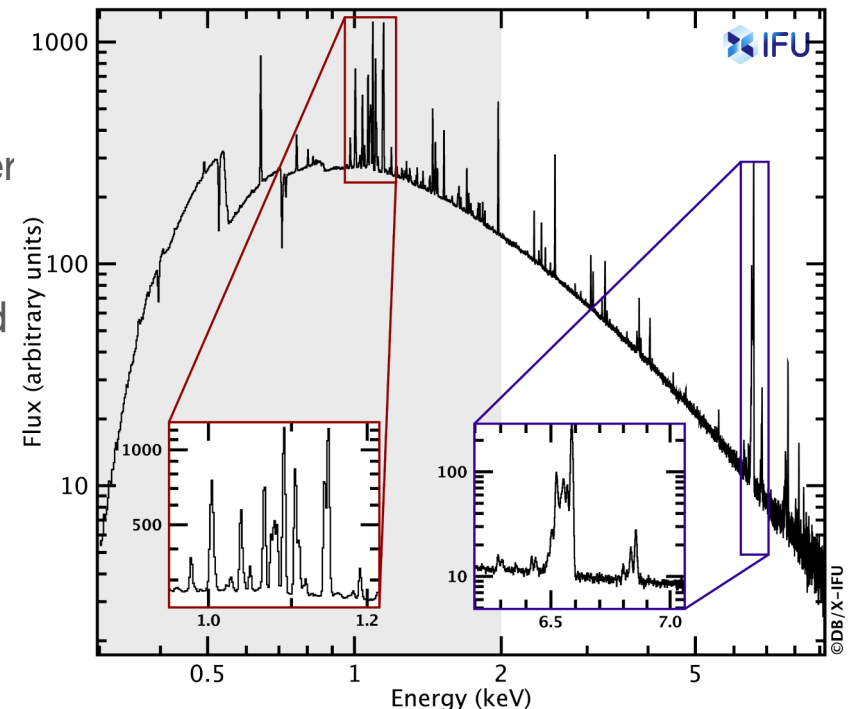
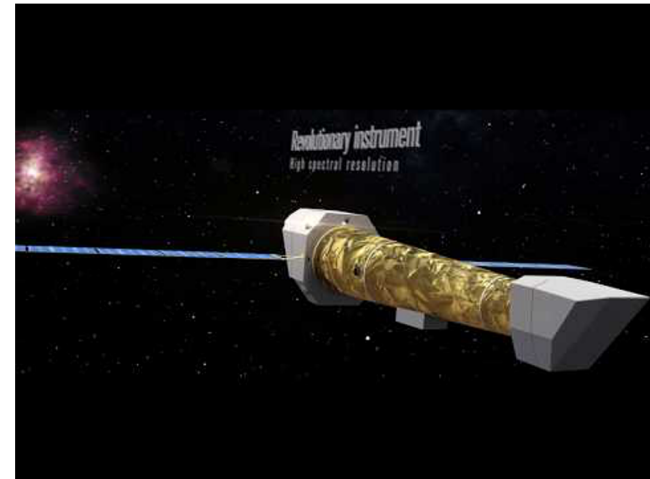
- *Athena* optics development:
  - Light-weight Si-pore optics
  - Grazing incidence optics with modified Wolter-Schwarzschild type I geometry optimised to provide wide flat field imaging
  - Vigorous development program on-going
- Expected Performance:
  - 5'' HEW on-axis
  - Graceful degradation off-axis  
HEW <10'' @ 30'
  - $\geq 1.4 \text{ m}^2$  effective area @ 1 keV  
 $0.25 \text{ m}^2$  effective area @ 6 keV (TBR)



Cosine/ESA

# X-ray Integral Field Unit (X-IFU)

- Cryogenic imaging spectrometer, based on Transition Edge Sensors, operated at 50 mK featuring an active cryogenic background rejection subsystem
- Key performance parameters:
  - 2.5 eV energy resolution <7 keV
  - FoV 5' diameter
  - Pixel size <5''
- Consortium led by IRAP/CNES-F, with Netherlands and Italy and further ESA member state contributions from Belgium, Czech Republic, Finland, Germany, Ireland, Poland, Switzerland and contributions from Japan and the United States
- Providing both spatially-resolved high spectral resolution and high count rate capability



Credits: X-IFU Consortium



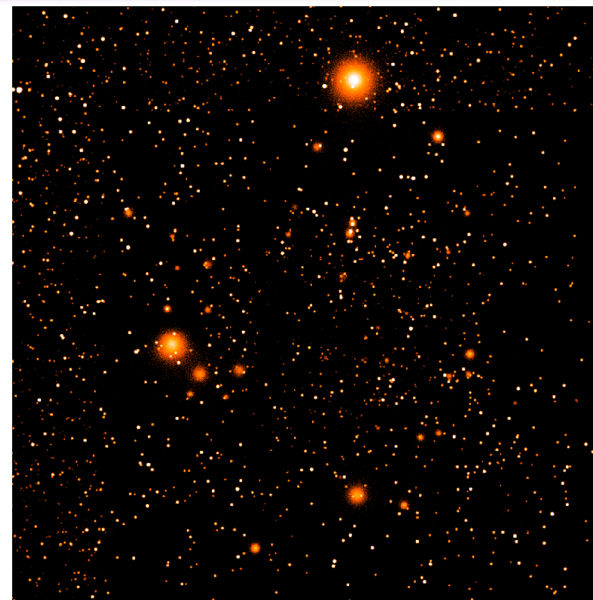
<http://x-ifu.irap.omp.eu/>



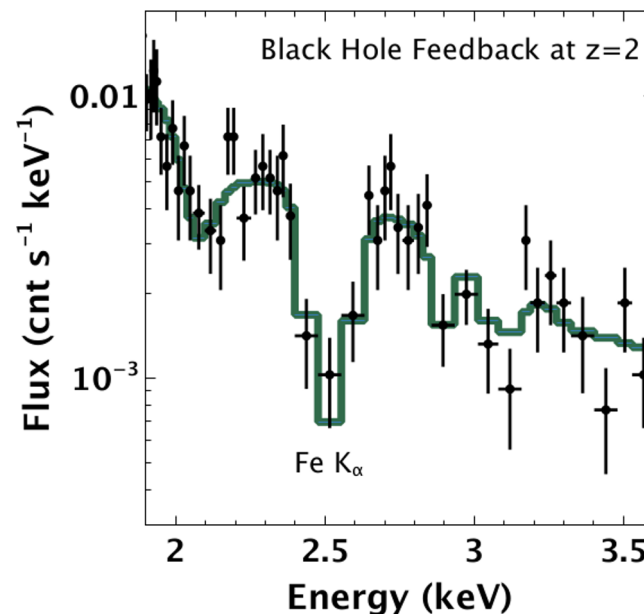
# Wide Field Imager (WFI)

- Silicon Active Pixel Detector based on DEPFET technology
- Key performance parameters:
  - $<80$  ( $<170$ ) eV spectral resol. @ 1 (7) keV
  - $2.2''$  pixel size (PSF oversample)
  - Field of view:  $40' \times 40'$  square
  - Separate chip for fast readout of brightest sources
  - Readout speed up to  $\sim 30$  MHz
- Consortium led by MPE, with other European partners (DE, AT, DK, FR, IT, PL, UK, CH, P & GR) and NASA
- Optimized for sensitive wide-field imaging and intermediate resolution spectroscopy, up to very bright sources

<http://www.mpe.mpg.de/ATHENA-WFI/>



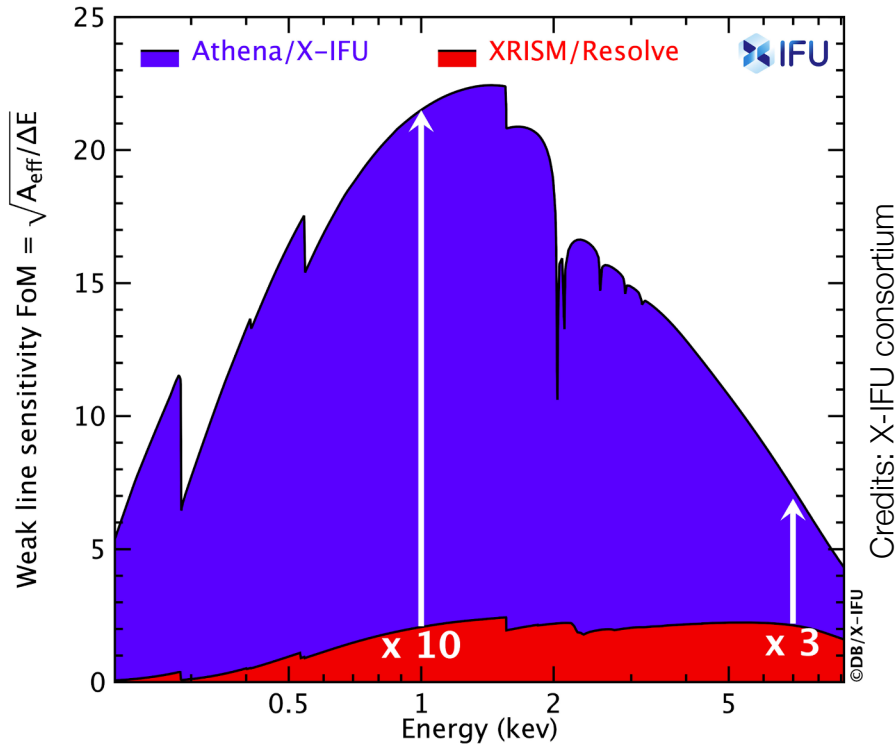
Credit: A.Rau/WFI team.



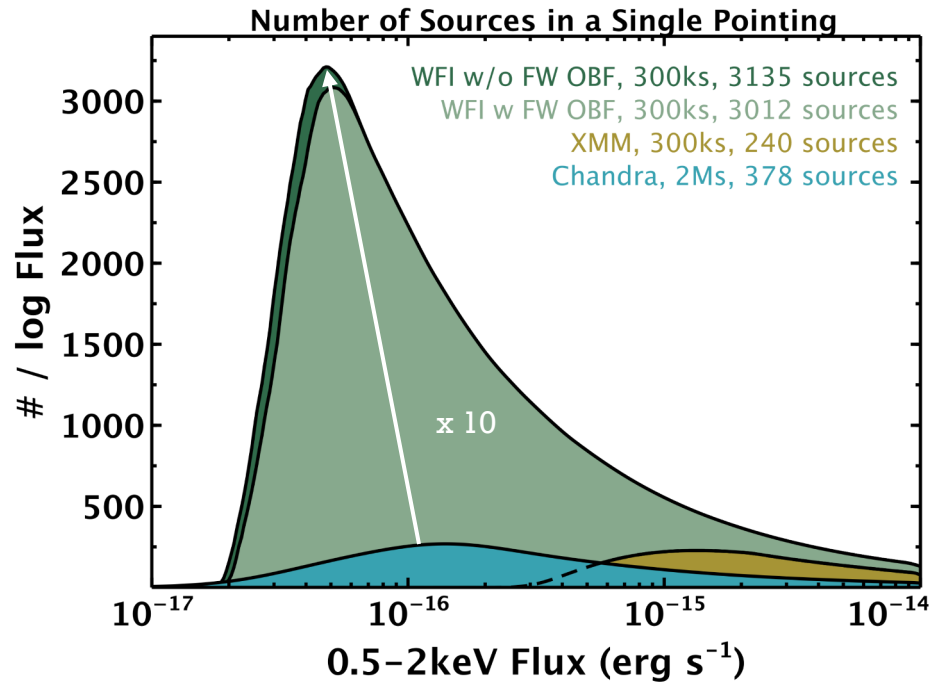
Credit: WFI team.



# Athena: a transformational observatory



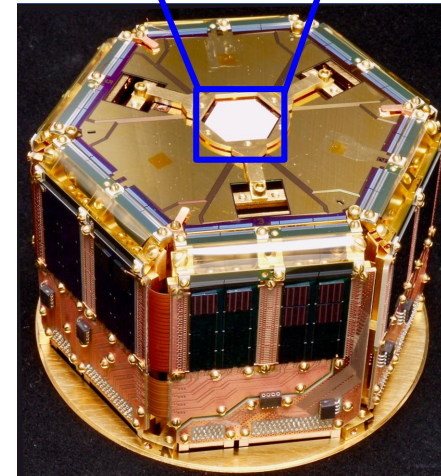
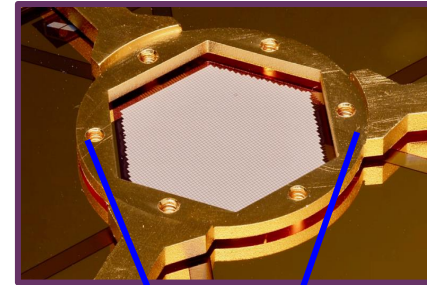
Weak line sensitivity comparison between X-IFU and XRISM



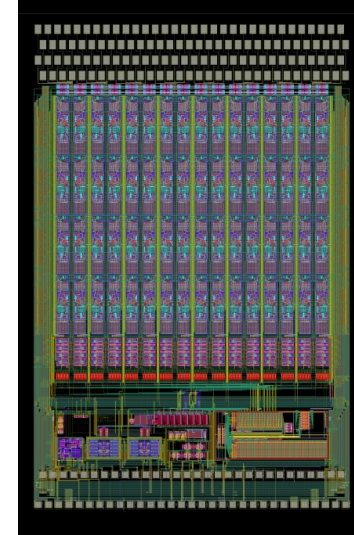
Number of sources per log flux that can be detected in a single pointing with WFI compared to XMM-Newton & Chandra

# NASA contributions to Athena

- **NASA's hardware contributions are in the \$100M-\$150M range**
- **Contributions consist of various enabling technologies:**
  - X-IFU Focal Plane Array (GSFC)
  - Use of NASA Testing Facilities (MSFC-XRCF) and involvement in mirror calibration
  - WFI VERITAS ASIC Design (Stanford)
  - WFI Background Analysis Model (BAM) Development (PSU, SAO, MIT, Stanford)
  - Vibration Isolation System (Moog SoftRide)
- **Additional contributions will include:**
  - Science Ground Segment support
  - US Guest Observer Facility
  - Preparatory Science and Guest Observer programs



X-IFU-FPA

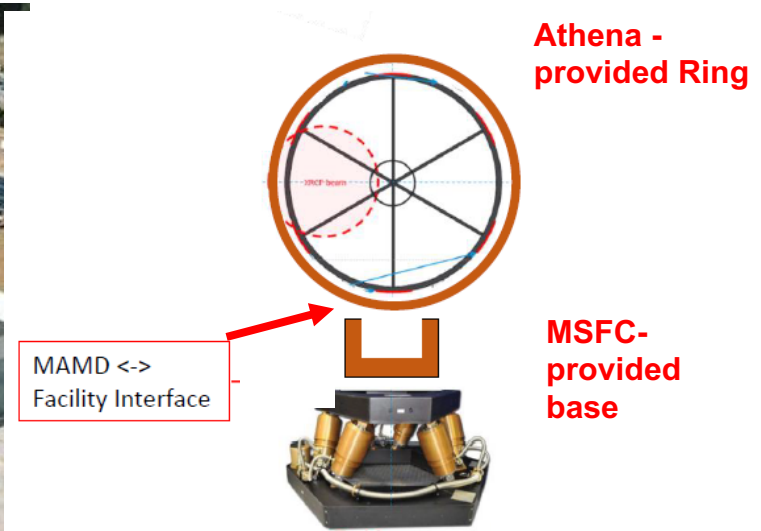


VERITAS ASIC Design



VIS  
(Moog SoftRide Uniflex)

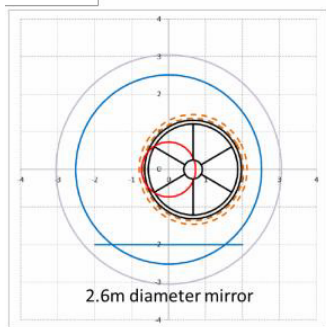
# X-Ray and Cryogenic Facility for Athena Mirror Calibration



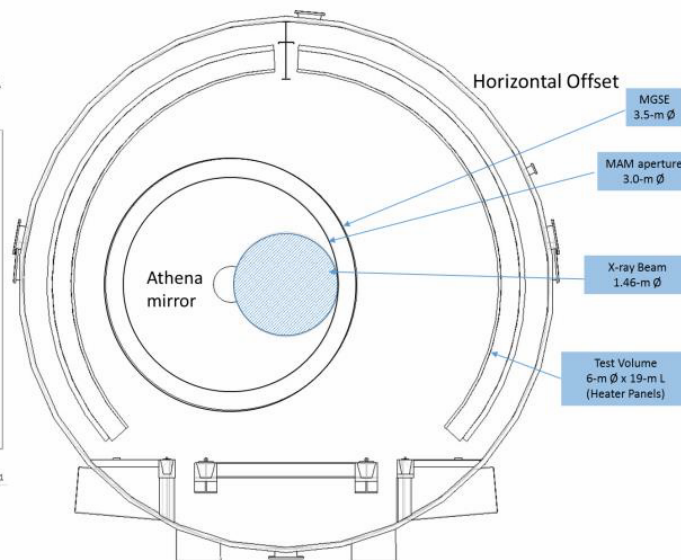
Currently planning MAMD verification (late 2021)

Primary interface between Athena MAMD assembly and XRCF MGSE defined

Partial Illumination of MA



Mark Ayre | 27/09/2017 | Slide 21



# NASA's contribution to Athena – Ground Segment

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- **NASA is planning to make a substantial contribution to the science ground segment. Planned contributions include:**
  - Participation in development of modules for the WFI and X-IFU pipeline processing
  - WFI processing might include background reduction and transient identification routines
  - X-IFU contributions will be based on XRISM pipeline
- **NASA will contribute to the calibration database**
  - X-IFU calibration database through planned pre-delivery calibration of focal plane array
  - Mirror calibration database through involvement in mirror calibration at the XRCF
- **Project science team is already involved in development of simulation software**



# Athena opportunities for US scientists

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- **US scientists are welcome to join Athena science working groups**
  - Organized by the Athena Science Study Team – no official project standing
  - Over 1,000 participants from around the world (over 100 from US)
- **NASA Athena Science Team:**
  - Consists of ~20 at-large scientists selected by NASA, hardware team representatives, and project scientists
  - Meets occasionally to guide NASA participation
  - Chairs are Jon Miller (Michigan) and Laura Brenneman (SAO)
- **Future opportunities include:**
  - NASA selection of US Col's for WFI and X-IFU
  - Guest Observer Program during active mission
  - Possible US share of guaranteed time



# Athena Project development: milestones

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- Instrument consortia were officially endorsed by ESA (Dec 2018)
  - Instrument Preliminary Requirements Reviews (I-PRRs) successfully passed
- Athena entered Phase B after passing Mission Formulation Review (Nov 2019)
- NASA Athena Study transitioned to a project (May 2020); currently in pre-phase A formulation
- Near-term upcoming events:
  - NASA KDP-A – May 2021
  - MAMD in XRCF – November 2021
  - NASA KDP-B – May 2022
  - Start of Mission Adoption Review– June 2022





# Outlook

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- *Athena* will be a transformational X-ray observatory
    - Designed to address the Hot and Energetic Universe science theme
    - Will impact virtually every corner of astronomy
  - It will be an essential part of the observational landscape in the early 2030s together with ALMA, ELT, SKA, CTA, etc.
  - Vibrant worldwide community supporting it
  - Substantial opportunities for participation by US community
  - Key milestones: Mission Adoption (Q2/2022) & Launch early 2030s
- Follow *Athena* on
    - Web: [www.the-athena-x-ray-observatory.eu](http://www.the-athena-x-ray-observatory.eu)
    - Twitter: [@AthenaXobs](https://twitter.com/AthenaXobs)
    - Facebook: [The Athena X-ray Observatory](https://www.facebook.com/TheAthenaXrayObservatory)
    - *Athena* Community Office email: [aco@ifca.unican.es](mailto:aco@ifca.unican.es)

